

Review of Cosmic Ray experiments with underground detectors

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Review of Cosmic Ray experiments with underground detectors

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The most important underground detectors addressing Cosmic Ray physics are described, with a special emphasis on the description of the used technology.

1. Introduction

The first generation of underground experiments ran during the '80s, triggered by the GUT theories. The most important results they obtained were the IMB analysis on proton decay, ruling out the minimal SU(5) model, the ⁸B solar neutrino observation by Kamiokande and the Supernova SN1987 detection. The impact on the technology development was relevant. Let me quote for instance the NUSEX experiment[1]: this detector proved the reliability of digital calorimeters based on plastic streamer tubes, opening the road to the construction of the hadronic calorimeters for the LEP experiments(ALEPH[2], OPAL[3]). IMB and Kamiokande showed that the water Cherenkov technique was robust while LSD pointed out the possibility of using liquid scintillator to search for Supernova explosion. The main limitation of these detectors was the collected statistics. The natural development was therefore the construction of similar detectors enlarged by an order of magnitude in volume or in area. The experience gained with NUSEX allowed the construction of MACRO[4], with an acceptance increased to more than two orders of magnitude. The Kamiokande and the IMB Collaborations joined Super-Kamiokande, reaching a mass of 50 Ktons and LSD inspired LVD at Gran Sasso, actually running with 600 tons of liquid scintillator. The most important questions are: how much the technology of these experiments is advanced? Do the most important technological limitations come from the large volume/area used or this kind of physics requires just a modest detector performance? Could they benefit of more

sophisticated techniques? I will try to answer to these questions reviewing the main underground detectors for Cosmic Ray physics actually running.

2. MACRO

Let me start with the MACRO experiment, located in the HALL B of Laboratori Nazionali del Gran Sasso. This is a multi purpose experiment for GUT magnetic monopole search, atmospheric and Supernova neutrino and Cosmic Ray studies. The detector consists of 14 horizontal layers of plastic streamer tubes(PST) and 3 horizontal layers of liquid scintillator(LS). Each side is closed with a sandwich of 6 PST and a layer of LS. The cell size of the streamer tube system has a cross section of $3 \times 3 \text{ cm}^2$, larger than the NUSEX one ($1 \times 1 \text{ cm}^2$). The readout was performed in NUSEX by using orthogonal pick-up strips, while in MACRO the wires and a layer of pick-up strips, forming an angle of 26.5° with the direction orthogonal to the wires, are read. The larger cell size, due to the dominant effect of the multiple scattering of the muons through the rock, doesn't affect significantly the pointing accuracy. Fig.1 shows the angle between multiple muons detected by MACRO. Since high energy multiple muons can be considered parallel within few milliradians, the distribution is the folding of the muon multiple scattering with the detector angular resolution. The 68% of the events has an angle $\theta \leq 1.1^\circ$ and therefore $\sigma_\theta = 1.1^\circ / \sqrt{2} \simeq 0.8^\circ$. The distribution is largely dominated by the multiple scattering, whose contribution at this depth is around $\sigma_\theta^{MS} \simeq 0.6^\circ$. This is a typical example in which the granularity of the detector is

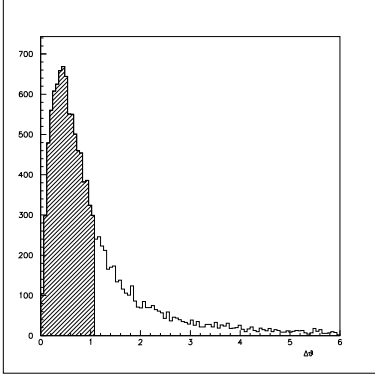


Figure 1. Space angle $\Delta\theta$ (degrees) between the direction of tracks in two muon events. The dashed area contains the 68% of the distribution.

limited by an external source of indetermination; an improvement of the detector space resolution would result just in a small improvement of the muon position measurement and pointing accuracy. Fig. 2[11] shows the MACRO magnetic monopole flux upper limit. Different techniques are used to identify a monopole in the various β regions explored. At $(10^{-4} \leq \beta \leq 10^{-3})$ the liquid scintillator informations are very helpful: the magnetic monopole signature is a train of photoelectrons, with a duration proportional to the monopole velocity. This is a delicate search, since background contamination could mimic the signal: a simple ADC/TDC system is not enough! MACRO takes advantage of a Waveform Digitizer System, with a sampling frequency of 200 MHz. The system is calibrated using LED light. Fig. 3 [12] shows a muon crossing three layers of liquid scintillator and the respective Waveforms. The study of upgoing muons, originating from neutrino interaction below the apparatus, requires high detector performance too. The discrimination against the much more abundant downgoing muons is obtained by using the time of flight system (TOF). The rejection factor required for

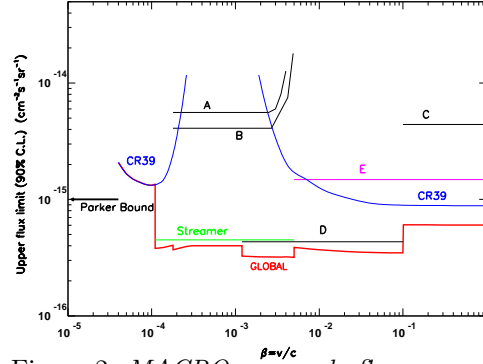


Figure 2. MACRO monopole flux upper limit.

this analysis is $\simeq 10^{-4}$. Fig. 4 shows the $1/\beta$ distribution obtained by MACRO. The left peak comes from upgoing muons, while the right peak comes from downgoing muons. The TOF resolution is better than 1ns, allowing a clear separation between the two peaks. Of course higher timing performance with TOF systems have been reached, for instance a resolution $\sigma_t \simeq 100$ ps has been obtained by the AMS TOF system[13]. Nevertheless, it must be stressed that in this case a $\sigma_t \leq 1$ ns resolution is obtained on a huge scintillator mass (600 tons), making use of 12 meters length counters, running for a long period, more than 8 years. As far as the physics results are concerned, such TOF system performance allowed the study of atmospheric neutrino anomaly. MACRO pointed out [14] a discrepancy between the real data and the Monte Carlo prediction for atmospheric ν_μ flux. The ratio between the data and the Monte Carlo prediction for upgoing muon flux was $R = 0.74 \pm 0.036(\text{stat}) \pm 0.046(\text{sys}) \pm 0.13(\text{theoretical})$. An improvement of the agreement between Monte Carlo and the MACRO data is found supposing an oscillation $\nu_\mu \rightarrow \nu_\tau$ or $\nu_\mu \rightarrow \nu_s$ with $\Delta m^2 = 2.5 \cdot 10^{-3} \text{eV}^2$ and $\sin^2 \theta = 1.0$. Further informations about neutrino oscillation could come from the measurement of the muon energy. Such a measurement for through-going muons is very difficult with the present genera-

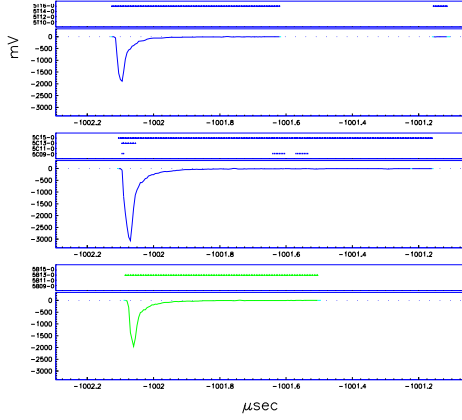


Figure 3. Muon signal in the MACRO scintillator obtained with the 200 MHz Waveform digitizer . tion of underground experiment. This is a typical situation in which a more advanced technology would have been useful. The average energy of upgoing muon is $\simeq 20$ GeV, while the average energy of downgoing muons at LNGS rock depth is $E_\mu \simeq 300$ GeV. A first attempt to measure the muon energy is due to the NUSEX and to the LVD Collaborations.

3. LVD

LVD is a multipurpose detector consisting of a large volume of liquid scintillator interleaved with limited streamer tubes in a compact geometry [10]. The apparatus has a modular structure that consists of aligned towers of 38 modules each. Every module contains 8 liquid scintillator counters of dimension $1.5 \times 1 \times 1$ m³ seen by three photomultipliers. Taking advantage of the L shaped detectors used as tracking system, LVD is able to measure the depth-intensity curve up to 20 Kmwe (Kilometers of water equivalent). As far as the measurement of muon energy is concerned, LVD measured the quantity $\langle \Delta E / \Delta L \rangle$ as a function of the rock depth h , where L is the track length in the scintillator counter and ΔE is the energy lost in the counters. For $h \leq 8$ Kmwe, this observable is expected to increase with h ,

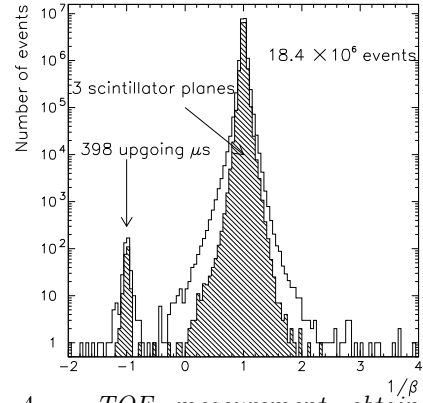


Figure 4. TOF measurement obtained by MACRO: right peak downgoing muons, left peak upgoing muons.

since a selection of higher rock depth corresponds to higher threshold for Cosmic Ray muon energy. For $h > 8$ Kmwe, the muon flux coming from atmospheric muon becomes negligible. Observed muons come from atmospheric neutrino interaction in the rock in the neighborhood of the detector: $\nu_\mu + N \rightarrow \mu + X$. The different origin of the muons, manifests for instance in the change of their average energy. This is small signal, difficult to observe. Fig. 5 shows $\langle \Delta E / \Delta L \rangle$ as a function of h . Although the statical error for high depth is large, at $h > 8$ Kmwe a clear decrease of $\langle \Delta E / \Delta L \rangle$ is visible in the LVD data.

4. Precision measurements

Cosmic ray detectors are usually supposed to perform measurements only with 10-20% accuracy. I would like to show two examples of small signals observed deep underground. Let me start with the measurement of the distribution of the distance between muon pairs detected deep underground, the so called "decoherence". This distribution depends on different cosmic rays features: the C.R. cross section, the muon parent mesons p_t distribution, the multiple scattering of the muons through the rock.

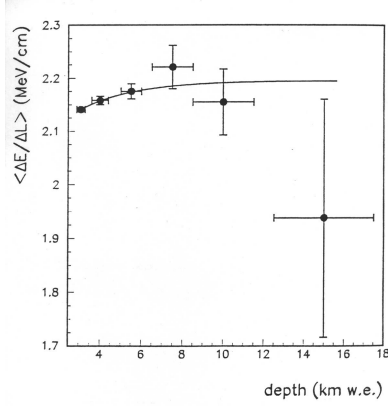


Figure 5. Measurement of $\langle \Delta E / \Delta L \rangle$ in the LVD scintillator as a function of the slant depth.

A special care has been devoted to the study of the tail at high distance of this distribution, to search for anomalous high P_t . On the contrary the surprise came from the low distance region. Fig. 6 shows the decoherence function observed by MACRO. A good agreement is evident between the MACRO data and the HEMAS Monte Carlo expectation. Nevertheless, a discrepancy of 34% is found for muon separation $D \leq 80$ cm. The same effect has been pointed out by the LVD Collaboration[18]: again the real data shows an excess respect to the Monte Carlo. An explanation of this effect has been proposed by the LVD Collaboration: muons at short distance can come from the direct muon pairs production by muons: $\mu + N \rightarrow \mu + N + \mu^+ + \mu^-$. It has been pointed out[21] that such process is suppressed, respect to the electron pair production, by a factor m_e^2/m_μ^2 only for small $v = E_\gamma/E_\mu$. At high v the cross section is not suppressed by such factor. Since the produced muon pair lies at low distance from the original muon, the results is an excess of events at short distance in the decoherence function. A data analysis from MACRO[17] shows that after the inclusion of this process in the muon transport simulation code, the agreement between data and Monte Carlo is restored. Another example of small signal pointed out in cosmic rays physics is the detection of photonuclear interaction of muons deep un-

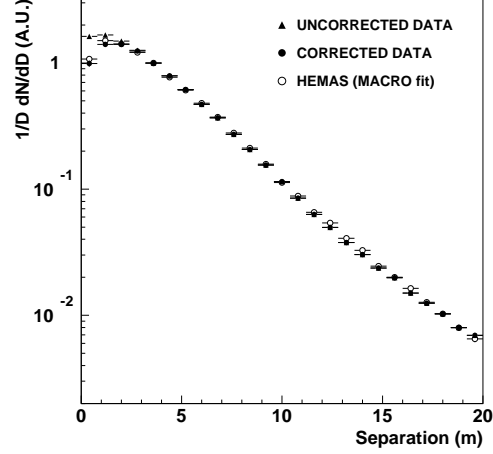


Figure 6. The low distance region of the MACRO experimental decoherence before and after the subtraction of the $\mu + N \rightarrow \mu + N + \mu^+ + \mu^-$ process.

derground. MACRO looked for charged hadrons with $E \geq 300$ MeV, produced in the rock surrounding the detector[17]. A data analysis based on 11,000 hours of live time, they found 1,938 candidate events over a total sample of 9,544,318 muon events. The result was expressed in terms of the ratio $R_{\mu+h}$ of the selected μ -hadrons events to the number of muon events in the same live time. After the subtraction of the background, they found for $R_{\mu+h}$ in real data and in the MC simulations :

$$- R_{\mu+h}^{DATA} = (1.91 \pm 0.05_{sta} \pm 0.03_{sys}) \cdot 10^{-4},$$

$$- R_{\mu+h}^{FLUKA} = (1.89 \pm 0.16_{sta} \pm 0.02_{sys}) \cdot 10^{-4},$$

$$- R_{\mu+h}^{GEANT} = (1.31 \pm 0.14_{sta} \pm 0.02_{sys}) \cdot 10^{-5},$$

confirming thus the obsolete treatment of the muon photonuclear interaction in GEANT3.15-3.21[19] pointed out in[20].

5. Super-Kamiokande

The Super-Kamiokande experiment is the underground detector with the largest mass actually running. Events produced in 50 Ktons of water are reconstructed by 11,146 PMTs. The main goals of the experiment are the study of ^8B solar neutrino, the search for proton decay and the study of atmospheric neutrino. As far as the at-

atmospheric neutrino is concerned, several measurements can be performed by SuperK: the ν_μ/ν_e ratio, the measurement of stopping/through-going muons and the measurement of the ν_μ flux as a function of L/E , where L is the distance travelled by neutrino and E is the neutrino energy. The analysis of the ratio $R=(\nu_\mu/\nu_e)_{data}/(\nu_\mu/\nu_e)_{MC}$ has been performed by several experiments. The NUSEX measurement[5] was affected by a large statistical error: $R=(0.96^{+0.32}_{-0.28})$, while the FREJUS Collaboration reported a substantial agreement between data and Monte Carlo[15]: $R=(1.00\pm0.15(stat)\pm0.08(sys))$. On the contrary a deficit of atmospheric ν_μ has been measured by two Cherenkov detectors. IMB[6] found a ratio $R=(0.54\pm0.05\pm0.11)$ and Kamiokande[7] measured $R=(0.60\pm0.05\pm0.05)$. The apparent mismatch between calorimetric and Cherenkov results, was recently restored by the Soudan II calorimeter. The Soudan II Collaboration reported [9] a ratio $R=(0.64\pm0.11(stat)^{+0.06}_{-0.05}(sys))$ based on an exposure of 3.89 kton-year, the largest for a calorimetric experiment. The analysis of SuperK was based on 33 Kton-year exposure[23]. They selected 4353 fully contained events and 301 partially contained. Only single ring events were used up to now. They splitted the events in two categories: sub GeV events ($E_{vis}<1.33$ GeV) and multi-GeV events ($E_{vis}>1.33$ GeV). They found $R=(0.63\pm0.03(stat)\pm0.05(sys))$ for the sub-GeV sample and $R=(0.65\pm0.05(stat)\pm0.08(sys))$ for the multi-GeV sample. These results, based on a very large statistical sample, confirmed the previous measurements. Nevertheless, the interpretation in terms of neutrino oscillation yields for Δm^2 a value $5\cdot10^{-4}\text{eV}^2<\Delta m^2<6\cdot10^{-3}\text{eV}^2$, while the best fit for the previous experiments gave a larger Δm^2 , for instance Soudan II found $\Delta m^2=1.1\cdot10^{-2}\text{eV}^2$. The most promising way to study neutrino oscillation using atmospheric neutrino seems to be the evaluation of ν_μ flux as a function of L/E : $\Phi_{\nu_\mu} = \Phi_{\nu_\mu}(L/E)$ [22]. Fig.7 shows the $(\Phi_{\nu_\mu})_{data}/(\Phi_{\nu_\mu})_{MC}$ as obtained by SuperK. The agreement between the real data (circles) and the Monte Carlo expectation(dotted line), obtained supposing a $\nu_\mu\rightarrow\nu_\tau$ or $\nu_\mu\rightarrow\nu_s$ oscillation with parameters $\Delta m^2=2.2\cdot10^{-3}\text{eV}^2$ and

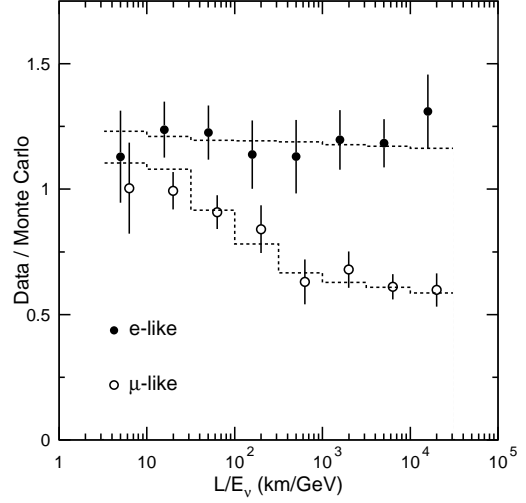


Figure 7. $(\Phi_{\nu_\mu})_{data}/(\Phi_{\nu_\mu})_{MC}$ as a function of L/E obtained by SuperK.

$\sin^2(2\theta)=1.$, is impressive. From a technical point of view, the SuperK analysis is based on single ring events only, therefore the reconstructed energy E of the event relies only on the muon energy. The precision in the measurement of L is also reduced, since the event kinematic is not completely defined. The most important goal of the next generation of atmospheric neutrino detector is the improvement of the L/E ratio measurement. Different ideas have been proposed. The measurement of the hadrons produced in neutrino events with a highly segmented calorimeter with mass $\simeq 10$ Ktons or the use of a massive calorimeter ($M > 30$ kton) to measure fully contained events with any track multiplicity.

6. Conclusion

Usually the underground detectors for Cosmic Ray studies are much more coarse than accelerator experiments. Such a low granularity comes from the high area/volume required, imposing an upper limit on the detector cost and on the number of electronic channels to be taken under control. Moreover sometimes the coarseness of the experiment is fixed by the working conditions. Nevertheless, a good technical performance is required to these experiments:

- **Long data taking.** Underground Observatory looking for Supernova neutrino (LVD, MACRO, SuperK) have to run for a long time (>10 years), avoiding any aging effect.

- **Flexibility.** An high flexibility is required to these detectors: the physics to be investigated spans in energy over more than 3 orders of magnitude. At $E \simeq 10$ MeV they look for Supernova neutrino while low energy hadrons produced in photonuclear interaction of muon have an energy of few hundreds of MeV. These detectors measure atmospheric neutrino with $E \simeq 1$ GeV, while the average energy of cosmic ray muons detected at Gran Sasso depth is $E_\mu \simeq 300$ GeV.

- **Precision measurements.** In some analysis an high rejection factor against background is required and signals as small as few 10^{-4} are successfully measured.

About the future the situation is quite different with respect to the '80s, when the most important lack of underground experiments was the poor statistics collected. The step forward was the construction of larger detectors, while now it is not possible to enlarge the underground detectors area/volume by an order of magnitude. Such mass increase is feasible only with underwater Cherenkov detectors. Moreover the underground space is limited and the safety rules became much more restrictive. Special care has to be devoted in the choice of the used materials. As far as the Cosmic Ray composition study with underground experiments is concerned, the interpretation of the results obtained by many experiments is nowadays much more urgent than the request for further experimental data. The lack of accelerator measurements at high energy and at high rapidity region, introduces large uncertainties in the Monte Carlo models for the Cosmic Ray shower development. The trend for the next generation of underground detectors seems therefore to be the construction of atmospheric neutrino detectors with reasonable mass and with an increased granularity. The ICARUS detector [16] for instance is foreseen to run within the 1999 at Gran Sasso with 600 tons. It will take advantage of the superb space resolution to perform an unambiguous analysis of the ν_μ/ν_e ratio. Other detectors have been proposed to improve

the L/E measurements for atmospheric neutrino. Together with the Long Base Line experiments, they will hopefully give an answer on the nature of the neutrino, using more advanced technology.

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